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# Low Power Circuit for EM Warning System Sensor

by John Russo, James Brent, and Marc Litz

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# Low Power Circuit for EM Warning System Sensor

**John Russo, James Brent, and Marc Litz**
**Sensors and Electron Devices Directorate, ARL**

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Low power sensors are important to the Army for purposes of monitoring infrastructure over the life-cycle of operation. Isotope batteries can power and operate compact, low power sensors for decades. A low power circuit has been developed to generate a repetitive radio frequency (RF) impulse, which will be used to indicate that a sensor has detected a target. This sensor circuit has been modeled and built to evaluate several isotope batteries in preparation. A parametric study of components in the circuit has been performed to minimize power consumption as a function of repetition rate and pulse width of the light-emitting diode indicator or RF impulse output. The results of simulation and measurement compare well. The minimum power characteristics are also identified in this report.

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# 1. Background

The goal of the project is to build a low power sensor circuit that can be used as a metric to evaluate an isotope battery. The significant function of an isotope battery is its usage as a power source that can release low level power (~1 mW) for decades. Isotope batteries are safe for low power applications. "Safe" is defined here in two ways: (1) quantities of isotopes used for the batteries do not require any licensing by the Nuclear Regulatory Commission (NRC), and (2) the radiation inherent in these quantities is below background levels. The typical efficiency for power output of isotope batteries is ~15%.[1] This is important to minimize the amount of isotope required and maximize power out per micro-Curie of material. A Curie is the unit of radioactivity defined as $3.7 \times 10^{10}$ events per second.

An example of an isotope battery we have built is described in section 1.1. Beta particles emitted from nickel-63 are collected within a P-N junction. Nickel-63 emits very low energy electrons (beta particles) with an average energy of 17 keV. These electrons are absorbed by silicon carbide (SiC) in P-N junctions.[2] The lattice structure of SiC is tighter than in Si. This makes SiC a more robust semiconductor, a radiation hard material more suitable for use as a direct energy converter. It has been shown to last longer in the presence of radiation. Low power circuit operation is essential in order to use these sources that can last for decades. This circuit will be used as a low-power sensor evaluation standard for isotope batteries under consideration.

Applications for low power sensors will continue to grow in importance. Low power sensors that can be buried in infrastructure for their life cycle (e.g., buildings, bridges, and roadways) would provide valuable warning of failure modes that could develop. The life-cycle requirement is in some ways similar to the need for long shelf-life batteries.[3]

## 1.1 Circuit Description

In the circuit description, a AAA battery is used instead of the isotope battery, which can have the same voltage as the AAA battery. The breadboard model of the circuit as built is shown in figure 1. The battery operates at a voltage of 1.5 V, which energizes a circuit. The circuit includes four transistors (one PNP and three NPN). The transistors operate as switches and current regulators. The transistors in the circuit are bipolar junction transistors (BJT). These transistors have three terminals—emitter, base, and collector. There are two P-N junctions that exist inside a BJT, which are base/emitter junction and base/collector junction. The NPN

[1]Litz, M.; Blaine, K.; et al. On-Demand High Energy Density Materials. *3rd International Energy Conversion Engineering Conference*, San Francisco, CA, 15–18 August 2005.

[2]Ngu, Y; Litz. M. *Study of Beta Radioisotopes Direct Energy Converters*; ARL-TR-4969;U.S. Army Research Laboratory: Adelphi, MD, September 2009.

[3]O'Brien, H. A. Radioisotope Applications. Oak Ridge National Laboratory. U.S. Atomic Energy Commission, 1962.

transistor is characterized by electrons being injected into the base region (emitter-base junction is forward biased). The NPN transistor controls the number of electrons coming in the base region. The minimum voltage for the transistor to turn on is 0.7 V. The PNP and NPN transistors are limited to ~200 mA max.

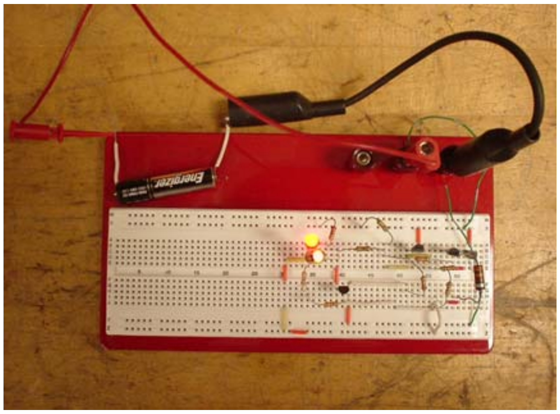

Figure 1. Breadboard of circuit simulation of low-power sensor.

In this circuit, PNP is turned on by the power source and collects the electrons from the current. The PNP signals the other NPN transistors, then signals the 100 µF polarized capacitor. The current charges the capacitor parallel to the battery and the light-emitting diode (LED). After the capacitor is charged up, it discharges to the LED. The LED starts flashing at 1.634 V. The LED signals the PNP that it has passed its threshold and has turned on. The PNP transistor signals the other three transistors that the LED has turned on, which repeats the whole process. The NPN triggers in the circuit, and the LED is turned off and out of the circuit for milliseconds, which explains the flashing light. When the voltage is dropped to 0.5 V, the transistor idles and the process is repeated. This process occurs so quickly that the only thing visible is the LED flashing.

Although the voltage passes the 1.634 V threshold of the LED, the voltage increases to about 1.8 V when it is flashing constantly in the circuit. The rest of the components in the circuit are resistors. These 10 resistors control and decrease the amount of voltage in the circuit. The polarized capacitor, 5.6 k, and 3.3 k resistors control and set the flash rate of the LED, and directly control the repetition rate and pulse width of the LED's pulse.

## 2. PSpice Modeling

The first step in this experiment was to construct a PSpice simulation to model the circuit. The circuit is shown in figure 2. The objective was to (1) verify that the circuit performs as expected, and (2) vary components in the circuit to understand the limits of operation and the minimum-power operation points. At the time of this effort, an exact model of the LED could not be

found. We instead used two diodes that modeled the voltage and current load that were similar to that of the LED (which we measured on the breadboard). The forward voltage threshold of each diode model was 0.7 V in the simulation. The actual LED in circuit has a forward voltage threshold of 1.634 V. By inserting two diodes into the simulation, the voltage closely matched the breadboard circuit. Measurements were taken of each component in the circuit with a Fluke-175 multi-meter for comparison. The voltage of the two diodes approximately matched the LED load of the breadboard. The current measured in the LED on the breadboard circuit was 22.22 mA. This differed from the simulation calculated current in the model of 38 mA. This known difference can still be used when comparing parametric studies in the modeling.

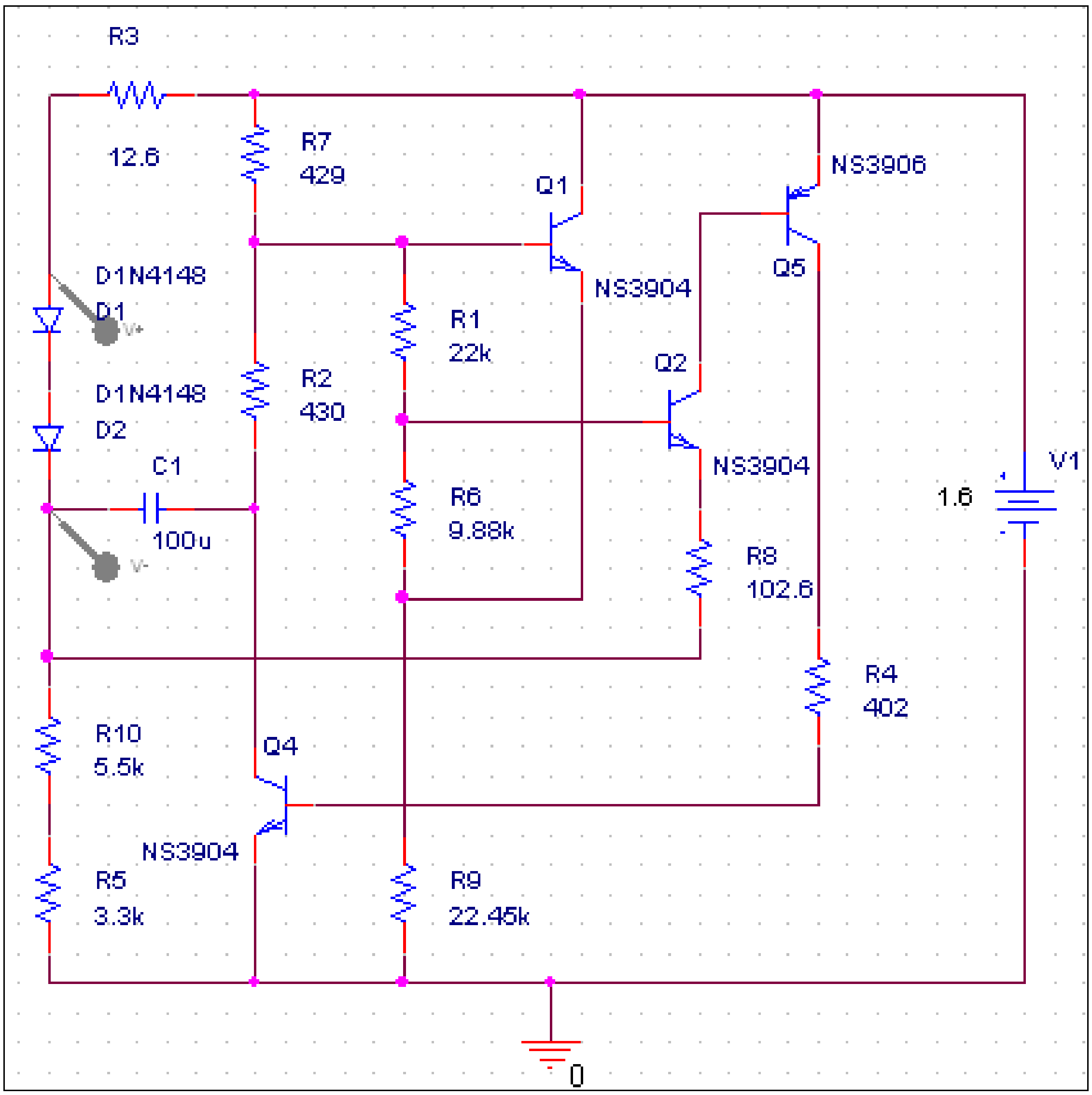


Figure 2. PSpice circuit model of low power sensor simulator. Resistor R3 at the top left controls the current in the diode. Capacitor C1 controls the repetition rate and pulse width.

The calculated response of the circuit is shown in figure 3.  The diode's output frequency is 2 Hz, reaching peaks of 1.65 V, while the peak-to-peak voltage calculates to 1.4 V, with a pulse width of about 3.5 ms.  The model calculated the voltage across the capacitor to be 678 mV peak, while the peak-to-peak voltage is 578 mV, with a pulse width of 400 ms.


Figure 3.  A repetition rate of 2 Hz is shown in the measured voltages above.  The voltage are calculated in the simulation across a) 100 uF capacitor C1 [0, 700 mV] and b) LED [0, 2 V].

Current probes were placed across the diodes in the model.  The calculated current waveform is shown in figure 4.  The current peak is 38.5 mA at 1.65 V.  The pulse width is ~2.3 ms for the current pulse.

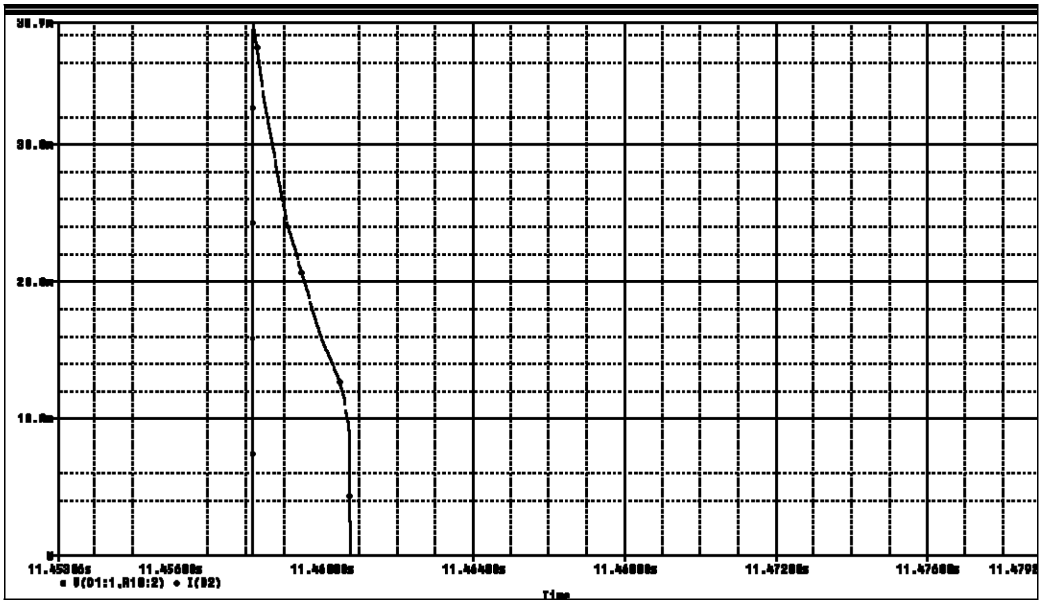


Figure 4. The current calculated in the LED is shown for single pulse in the repetitive train. The pulse width shown is ~2.3 ms. The peak amplitude is 38.9 mA.

## 2.1 Parametric Variation of Components

Three components were varied in the following investigation—the capacitor C1, the diode resistance R3, and the repetition rate resistance (R10 and R5). The circuit parameters that are of interest in this study are power dissipated in the circuit, the pulse width, and the repetition rate. The results are described in the following subsections.

### 2.1.1 Capacitance (C1)

After verifying the current and voltage of the LED (diodes), a parametric study of capacitors was performed to identify the change in pulse width and repetition rate. The capacitance was varied with four values: (1) 47 µF, (2) 220 µF, (3) 470 µF, and (4) 1000 µF. The resulting output repetition rates are 4, 0.7, 0.3, and 0.2 Hz, respectively. The smaller capacitance modeled using PSPICE resulted in an increased repetition rate (see figure 5). However, the pulse width decreases with a smaller capacitor. Measurements of the dependence of repetition rate with capacitance variations are confirmed and shown in figure 6. The measured reduction in repetition rate with increasing capacitance is confirms the simulation trends. The reduction in repetition rate has impact on the energy consumed by the sensor circuit.

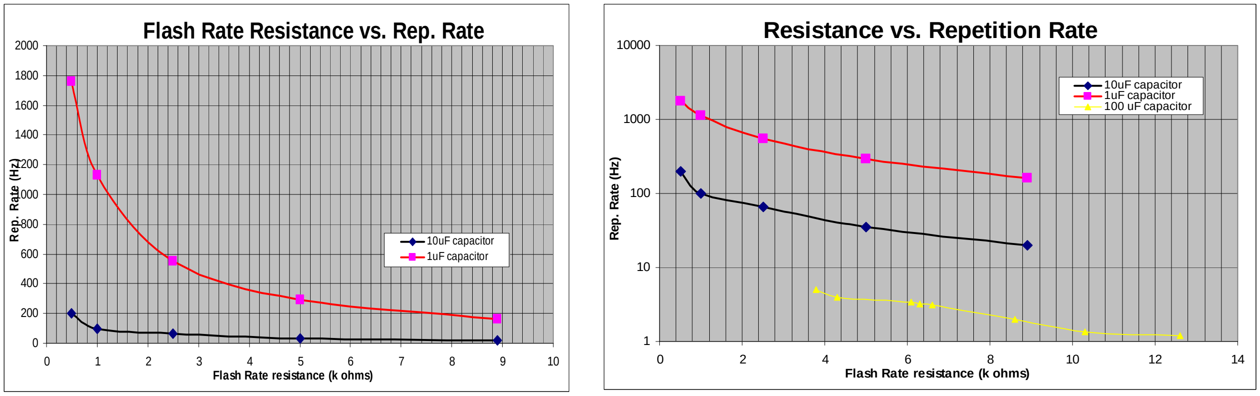


Figure 5. The graph shows the relationship with flash rate resistance (R10 & R5) and repetition rate of the diode resulting from numerical calculations.

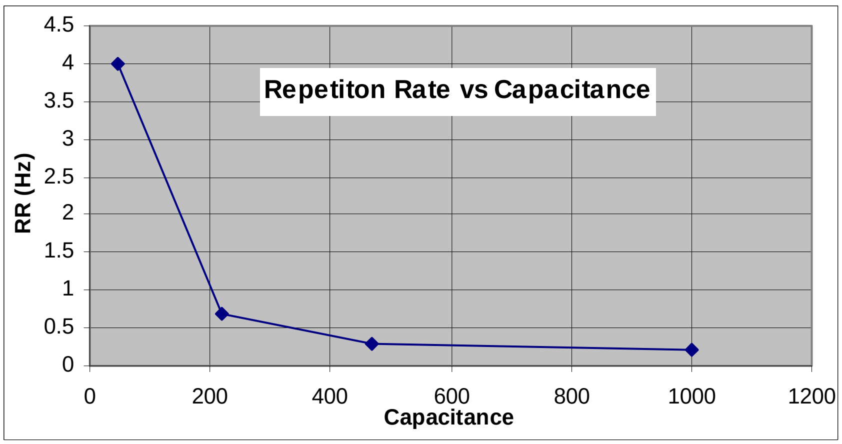


Figure 6. The repetition rate of the sensor decreases with increasing capacitance as measured in the circuit.

### 2.1.2 Resistances (R10 and R5)

A parametric study of resistance was performed on resistors R10 and R5. These components can be seen in the circuit diagram at the lower left-hand corner of figure 2. As the resistance increased, the repetition rate decreased. The pulse width of the LED/diodes and the voltages across the LED/diodes do not change significantly. The two resistors were each replaced four times with 500 ohms, 1 k, 3 k, and 7 k resistances. The resulting eight data sets are shown in figure 7. The repetition rate over this small resistance change varies only from 0.2 Hz to 5 Hz. The capacitance and the diode resistance R3 are held constant at 100 μF and 12.6 Ω, respectively.

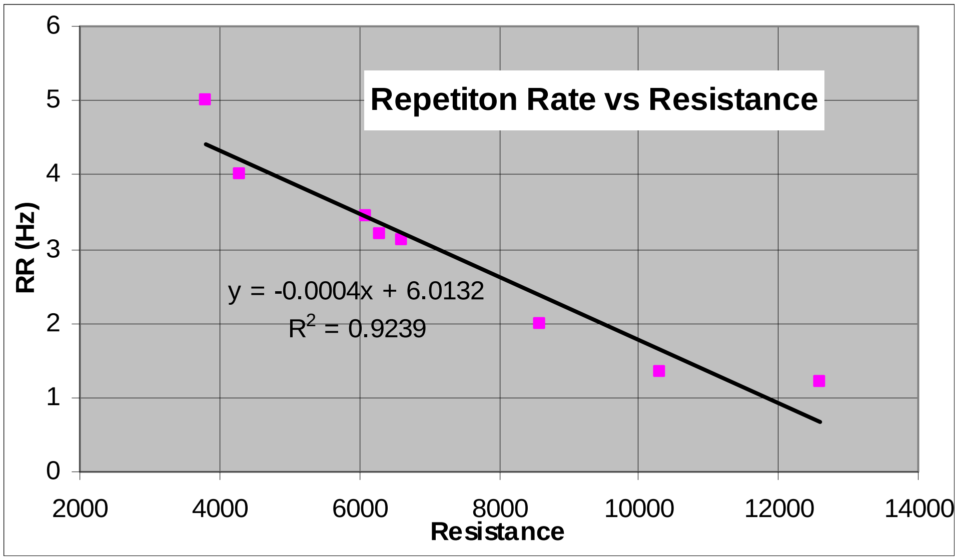


Figure 7. The resistors R10 and R5 were varied in the model. The resulting repetition rate is shown with a linear trend line drawn with respect to resistance.

Physically combining R10 and R5 had no effect on the circuit. There was no change when the two flash rate resistors (R10 and R5) were combined to add up to 8.9 k. Combining these two resistors would make it easier to change and control the values in order to see the change in repetition rate of the diode, power dissipation of the diode, and the pulse width.

### 2.1.3 Diode Resistor R3

This resistor does not affect the repetition rate. The significance of this component is in the overall power of the circuit. Current through the diodes can be controlled by the diode resistor (R3 in figure 2) the 12.6 Ω resistor. Diode current decreases with increasing resistance in the Diode resistor R3. The effect on circuit power will be discussed in section 2.2. Changing this resistor's values did not change the flash rate of the LED/antenna loads, or the pulse width, only the current draw.

## 2.2 Power Dissipation

The power (P) dissipated in the circuit can be determined by measuring both the current (I) and the voltage (V), i.e., $P = IV$. We would like to minimize power consumed in the circuit in order to make it last long. The practical aspects of the circuit that will be determined by the application are the power requirements, the pulse repetition rate, and the pulse width of the LED/antenna load. These parameters are not mutually exclusive; in fact, they are all related to each other. The operational scenario of the sensor will determine the best tradeoff of these three characteristics: power, pulse width, and pulse repetition rate.

We wish to identify the components that contribute most to power loss in the circuit. The diodes consume 64 mW of power, each diode consuming 32 mW. The capacitor C1 consumes about 28.1 mW; the 12.6 Ω resistor (see R3 in figure 2) consumes ~19.5 mW. To decrease the power

dissipation of the resistor, the diode resistance can be increased. When increased to 15 Ω, the power dissipation of the resistor decreased to 18 mW. This alteration left the battery drain at 65 mW and a single diode drawing 27 mW. Decreasing the resistance to 1 Ω decreased the power dissipated in the resistor to 12 mW and the total battery drain to 195 mW, while a single diode increased to 110 mW. Further measurements concluded that changing that resistor did not change the flash rate of the diode and capacitor.

Another observation was that the two diodes have the same repetition rate, but different power dissipation. Results showed that a single diode has a small comparison with the LED in the actual circuit. However, changing the resistor's values did change the current of the diode a small amount. The column consumption is a measure of the ratio of power radiated by the LED/antenna, divided by the power used by the remainder of the circuit.

Variation of resistor R3 changes the current in the LED/diodes and resistor. As resistance increases in R3 (see table 1 column 2), the power consumed by the diode (see column 3 table 1) decreases. This effect is shown graphically in figure 8.

Table 1. The diode resistor (R3) can be increased to minimize the power consumption to 10 mW.

| | **Changing the Value of the Diode Resistor (12.6 ohms)** | | | | |
|---|---|---|---|---|---|
| | **Resistance (ohms)** | **Power Dissipation Diode (mW)** | **Power Dissipation Battery (mW)** | **Current of Diode (mA)** | **Consumption %** |
| | 1 | 109 | 195 | 117.000 | 55.8 |
| | 10 | 38 | 82.3 | 45.800 | 46.1 |
| **Constant in model** | **12.6** | **32.1** | **75** | **38.500** | **43** |
| | 100 | 5.6 | 23.4 | 7.820 | 24 |
| | 1000 | 0.6 | 11.9 | 1.039 | 5 |
| | 10000 | 0.063 | 10.5 | 0.122 | 0.6 |
| | 80000 | 0.0072 | 10.3 | 0.017 | 0.069 |
| | 100000 | no pulse | no pulse | n/a | n/a |

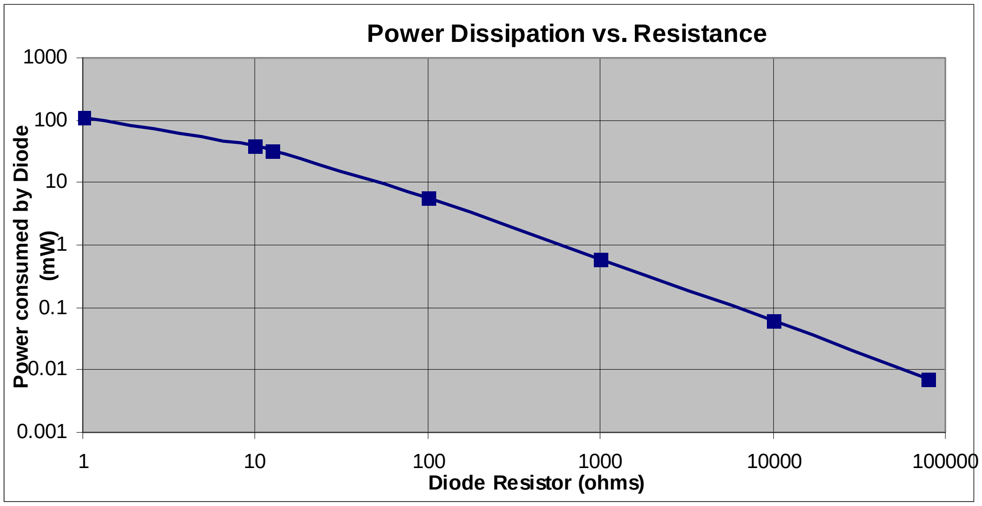


Figure 8. The graph shows the relationship between power dissipation and resistance value in resistor R3.

Increasing the capacitance (C1) decreased the repetition rate and the pulse width. Increasing resistors R10 and R5 decreased the repetition rate. The diode resistor (R3) stayed constant with normal value of 12.6 Ω. Figure 7 shows the relationship between the flash rate resistors (R10 and R5) and the repetition rate. As the flash rate resistor increases, the repetition rate of the diode decreases. The measured data of figure 7, that are tabulated in table 2, identify the 10 measured points, and serve to identify the noted trends towards reducing the power drain in this circuit for optimized use in sensors.

Table 2. Changing the flash rate resistors (R10 & R5) using smaller capacitance.

| **10 µF Polarized Capacitor** | | | | | | |
|---|---|---|---|---|---|---|
| **Resistance (k ohms)** | **Rep. Rate (Hz)** | **Voltage (V)** | **Current (mA)** | **Power Dissipation (mW)** | **Pulse Width (ms)** | **Capacitor (µF)** |
| 8.9 | 20 | 1.63 | 39.3 | 32.2 | 1.3 | 10 |
| 5 | 35 | 1.627 | 38.4 | 31.2 | 0.7 | 10 |
| 2.5 | 66.3 | 1.615 | 35.4 | 28.4 | 0.55 | 10 |
| 1 | 100 | 1.595 | 30.9 | 24.5 | 0.4 | 10 |
| 0.5 | 200 | 1.57 | 25.7 | 20.3 | 0.02 | 10 |
| **1 µF Polarized Capacitor** | | | | | | |
| 8.9 | 160 | 1.635 | 40.5 | 33 | 0.6 | 1 |
| 5 | 290 | 1.62 | 39.5 | 32.3 | .005 | 1 |
| 2.5 | 550 | 1.61 | 35.3 | 27.4 | .002 | 1 |
| 1 | 1,130 | 1.609 | 32.3 | 25.8 | .001 | 1 |
| .05 | 1,760 | 1.576 | 27.7 | 22 | .0001 | 1 |

The purpose of these measurements was to explore the use of this circuit for high repetition rate operation. The LEDs can be replaced with wideband antenna. Under these circumstances, the output signal should be configured for kilohertz repetition rate operation and micro-second pulse

widths. There are several applications that use high frequency warning sensors. By reducing the capacitance and resistance, the repetition rate can be increased to 1,760 Hz using very small amounts of current.

# 3. Circuit Description

The circuit used in this sensor simulator is a discrete element replacement for the circuit found in the LM3909 LED flasher oscillator. The application for this circuit is as follows—if a sensor/detector attached to the circuit goes positive, then the flasher will be intiated. The LED in this circuit could just as easily be replaced by a small teardrop-monopole antenna. The resulting mW power-levels of radio-frequency (RF) radiation will identify activity, and would be a good sensor circuit for a wireless array.

## 3.1 Components of Circuit

### 3.1.1 Transistors

The four transistors in the circuit are key components. In circuits, transistors are semiconductor devices that are used as current regulators and switches. They are used to amplify or switch electronic signals. PNP and NPN represent which semiconductors are in the middle of the two conductors. Transistors are considered very useful and effective in circuits because they are small and have minimal weight, allowing the development of miniaturized electronic devices. They also have highly automated manufacturing processes, which allow for mass production (low per-unit cost). Another advantage is lower possible operating voltages, making transistors suitable for small, battery-powered applications (AAA battery and isotope battery). They have no warm-up period for cathode heaters required after power application, and they consume a small amount of power and have greater energy efficiency. Transistors can amplify, producing an output signal with more power in it than the input signal. The additional power comes from an external source of power. Another advantage of a transistor is that it has an extremely long life—some transistorized devices produced more than 30 years ago are still in service.

### 3.1.2 LED

An LED is a semiconductor diode that emits incoherent narrow-spectrum light when electrically biased in the forward direction of the P-N function. The diode used in the circuit is a red LED. These devices are typically used as small indicator lights in electronics. They are also used in high power applications such as flashlights. The potential difference (Vf) of the LED can vary from 1.3 V to 2.1 V. The diode does not turn on and open until the voltage passes through a threshold, which is shown in figure 9.

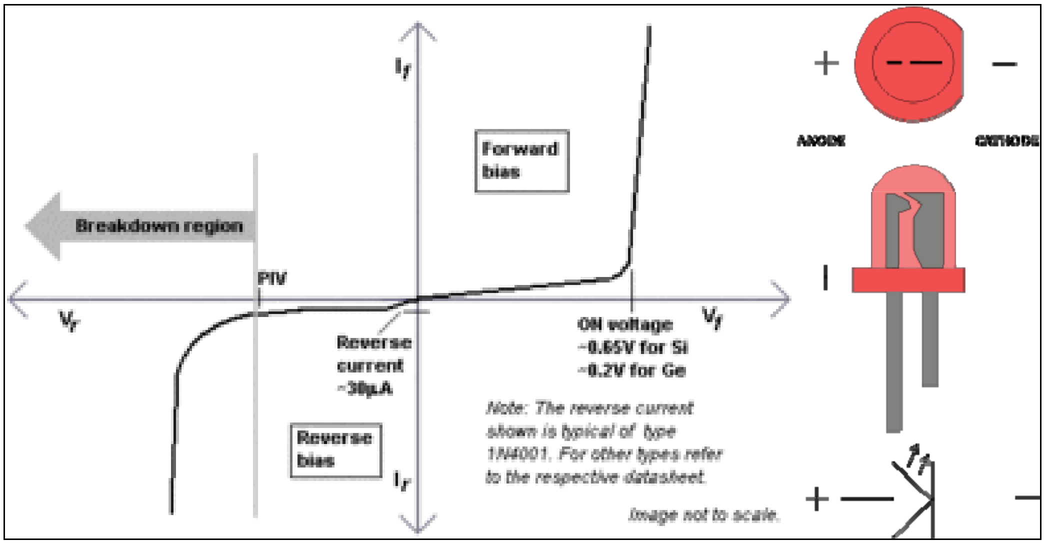


Figure 9. The IV curve for the LED shows the voltage threshold graph and the polarity of the red LED.

Current flowing in the forward bias direction of an LED generates light. Reversed bias flow generates no light. The LED can be operated with alternating or bi-polar current and voltage, but the diode will only light with positive voltage. This causes the LED to turn on and off at the frequency of the AC supply. The minimum voltage of the LED as modeled in the circuit is 1.3 V at 0.024 mA. The maximum voltage tested in the circuit is 1.8 V at 22.22 mA. The minimum current for the LED to be lit is 0.03 mA, with a voltage of 1.5 V. This measurement was taken outside of the circuit. In the circuit, the LED begins flashing at 1.634 V at .8 mA. When the LED starts constantly flashing in the circuit, the voltage is 1.8 V at a current of 22.22 mA.

### 3.2 Circuit Logic

There are two states of operation for the sensor simulator circuit. The two states are identified when the circuit is 1) charging and 2) flashing. To get a better understanding of the circuit (see figure 10), we must realize that the transistors in the circuit perform as current switches and regulators. State 1) is when the switch is open and the capacitor in the circuit is charging. The current from the battery flows through the resistors. The capacitor charges in series with the battery and parallel with the LED. The capacitor charges to supply the voltage.

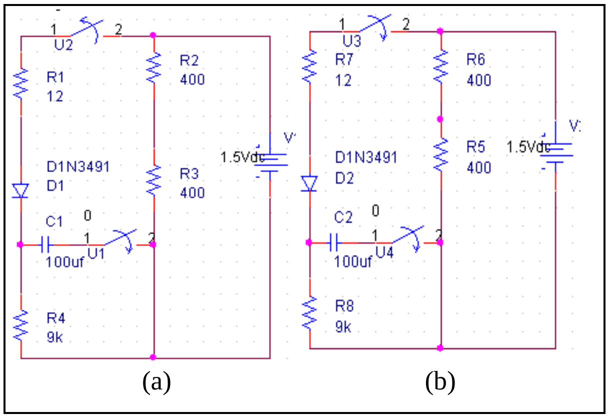


Figure 10. The circuit operation can be divided into two operational modes. The charging cycle (a) and the voltage doubled flashing cycle (b).

State 2) is when the switch is closed. The current is now flowing through the LED and the circuit is flashing. The capacitor discharges in series with the battery and the LED. This mode of the flasher circuit is when the LED flashes. At this point, both the battery voltage and the voltage across the capacitor are available to drive the LED. This process enables voltage multiplication. The voltage multiplies because the capacitor is charged up to 1.5 V, then it discharges across the LED. After being discharged, the battery is still sending current through the circuit, but into the charging of the capacitor. This, in turn, adds the 1.5 V from the cap and the battery, and the voltage is increased to pass the diode's threshold. The capacitor does not charge to full supply voltage. The oscillator switches before the capacitor can be reversed-biased.

### 3.3 Experimental Results

The circuit was constructed on a breadboard (see figure 1). Measurements were performed to identify voltage and current across significant components in the circuit that were involved in this parameter study. The components of interest included the diode resistor R3, the repetition rate resistors (R10 and R5), and the capacitor C1. After recording voltage and current, measurements were made to identify how much power and energy are needed to turn on and sustain the circuit for longer than merely a few cycles. By understanding of the effects of varying these components, an understanding of the trade-space could be developed for the application of this sensor/circuit.

The measured characteristics of the LED in the circuit shown in figure 2b are (a) frequency output of the LED is 2 Hzm, (b) peak to peak is 1.52 V, and (c) a pulse width 2.4 ms. The measured characteristics of the capacitor shown in the circuit in figure 2a are (a) frequency of the capacitor charge is 2 Hz, (b) maximum voltage of 700 mV, and (c) a pulse width is 500 ms.

The current in the LED is small enough that it is difficult to measure directly on the breadboard. The current through the LED was deduced from the current measured in the adjacent resistor R3. The minimum voltage to barely light the LED was 1.3 V at a small current of .024 mA. When

the current is at .03 mA, the LED is lit with 1.5 V. The LED begins flashing at 1.634 V at .8 mA. In the circuit, the voltage is 1.8 V at 22.22 mA. The resistor R3, closest to the LED, which was the 12.6 Ω resistor, was used to measure the voltage. Voltage across the resistor was 280 mV. So, by dividing the voltage by the resistance, we get the current for the LED (280 mV/12.6 Ω = I = 22.22 mA). So, the maximum voltage tested in the experiment was 1.8 V at 22.22 mA.

The capacitor was varied in order to change the pulse width of the output. The four different types of capacitors in the circuit were the same values as modeled in PSpice: 47 µF, 220 µF, 470 µF, and 1000 µF capacitance. However, the predicted observation was that these measurements were going to be different than in the simulation, as different diodes were used in simulation from those used in the actual circuit. This one variation is a significant variable in our experiment. The final outcome of this test determined that the larger the capacitor, the slower the flash rate and the longer the pulse width.

As the capacitance increases, the pulse width increases and becomes wider. This trend is shown the series of oscilloscope traces shown in figure 11. The power consumed in the circuit is calculated by P = IV. We then calculated Energy (E = P*t). Figure 12 illustrates the repetition rate and the pulse width of the LED. The power drain from the source is between 35 to 40 mW, when varying the five different capacitors that were measured in the circuit: 47 µf, 100 µF, 220 µF, 470 µF, and 1000 µF. Table 3 shows that as capacitance increases, repetition rate and pulse width decrease; the current and power, however, gradually increase. The relationship of capacitance, pulse width, and repetition rate are shown graphically in figure 12. The flashing of the LED starts slowing down because it takes the capacitor longer to discharge, which explains the slow blinking of the red LED.

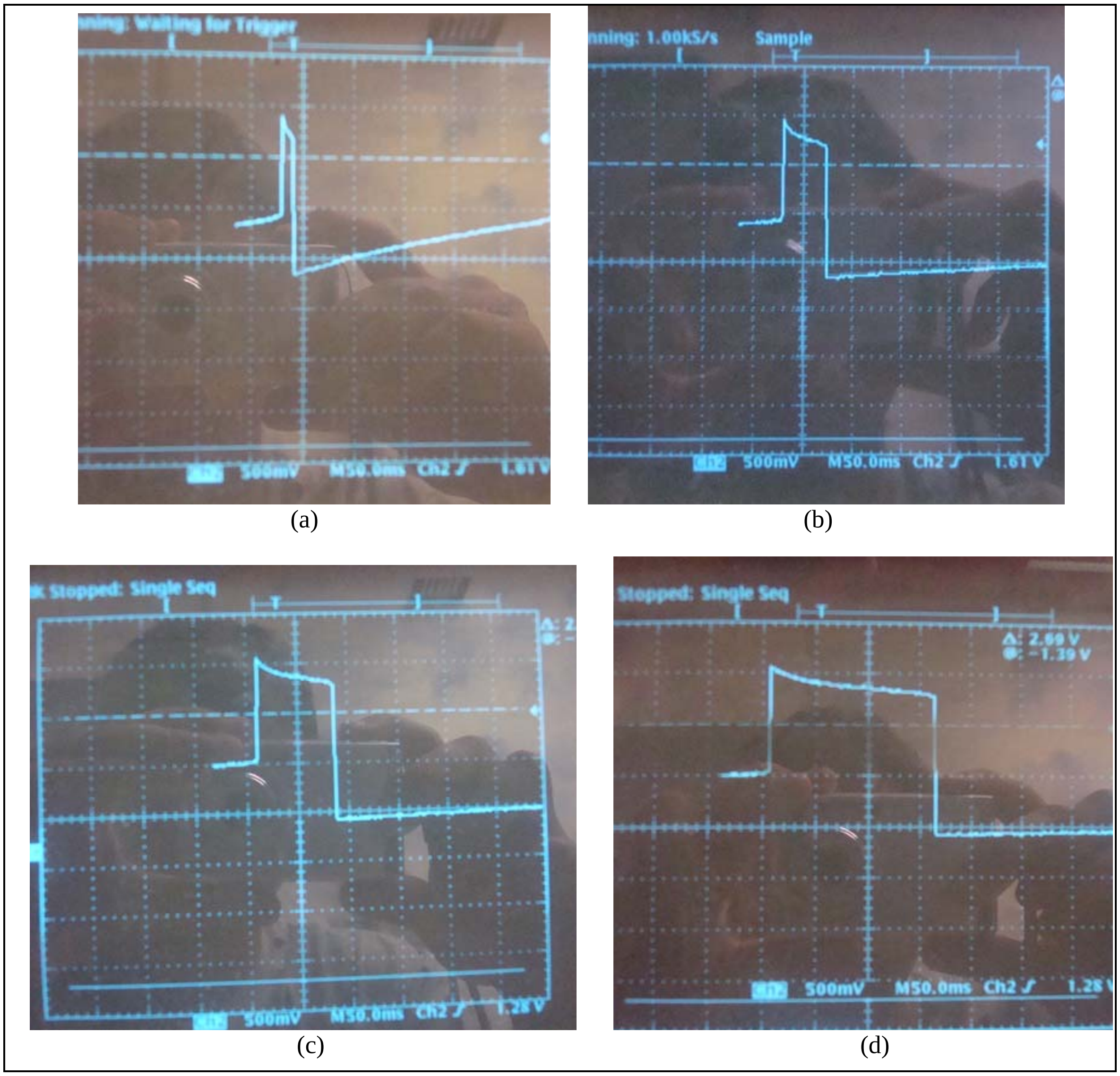


Figure 11. Pulse width variation of the output is achieved by varying the capacitor C1. The oscilloscope traces above all use a 50 ms/division setting. The capacitors are varied from (a) 47 µF, (b) 220 µF, (c) 470 µF, and (d) 1000 µF. The corresponding pulse widths are 19, 55, 80, and 152 ms.

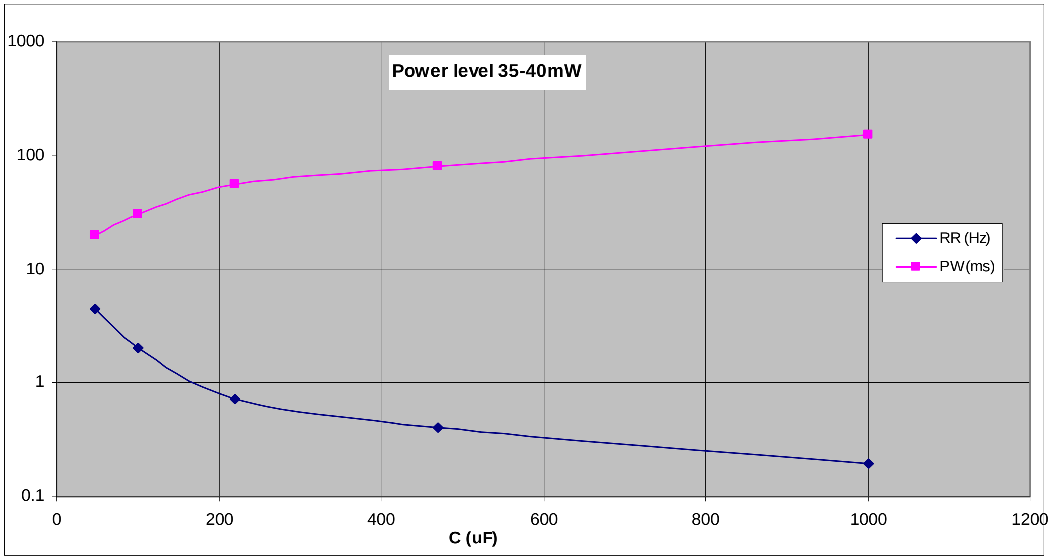


Figure 12. The graph shows the relationship of capacitance, PW, and repetition rate.

Table 3. Changing capacitance in LED circuit.

| Capacitor (µF) | Rep. Rate (Hz) | Pulse Width (ms) | Measured Current (I) (mA) | LED Power (mW) | Energy (J) |
|---|---|---|---|---|---|
| 47 | 4.444 | 20 | 21.43 | 35.02 | 3.11 |
| 100 | 2 | 30 | 22.22 | 36.31 | 2.18 |
| 220 | 0.7142 | 55 | 23.175 | 37.87 | 1.49 |
| 470 | 0.4 | 80 | 23.492 | 38.39 | 1.23 |
| 1000 | 0.196 | 152 | 23.81 | 38.91 | 1.16 |

## 4. Comparison of Modeling and Circuit

A pair of D1N4148 diodes was used in the circuit to simulate the LED. At the time of the work, no LED was available in the library of P-spice components. The diodes used in the model have slightly different current loading characteristics than the LED. That is the most significant difference between experiment and modeling. The repetition rate compared well between the model and experimental LED circuit, as it was very similar when the capacitance was changed in both model and the circuit. This is because the transistors and capacitors in both procedures signal at the same time. The flash rate is 2 Hz when the original 100 µF capacitor was used. Another comparison that worked well was that voltage across the diodes and LED were very similar in value. The diode voltage threshold (for both in series) is 1.4 V, and the LED's voltage threshold is about 1.5 V for it to turn on. The maximum peak in the PSpice model is 1.65 V (pulse width is 3.5 ms), and the maximum peak in the circuit is about 1.8 V (pulse width is 2.4 ms).

The main differences in this experiment are the current and power dissipation. The current across the two diodes is 38.5 mA. The current across the LED is about 22.22 mA. The power is different because of the different currents running across the diodes and LED (P = IV). The main reason for this difference was that the LED model was not found or located in PSpice. However, in further evaluations, we will solve that problem by locating the LED model, so that the simulation will compare better to the LED circuit.

## 5. Conclusions

In concluding this experiment, we found that the tasks of building this low power sensor simulator and measuring certain parts in the circuit were successful. We fulfilled the job of building a circuit that works as a LED flasher/oscillator. The main task in this project was to find how much power is drawn in the circuit. After finding the power, we were supposed to find ways to create less power drawn from the battery so we could create a very low power sensor. We were able to build a circuit on PSpice, so we could observe the parameters of the circuit. We built the circuit in PSpice using simple components in a circuit. We made several measurements in PSpice and compared them to the actual data later in the experiment. The data was very similar to the data recorded in the actual circuit. The LED's frequency was 2 Hz, mirroring the polarized capacitor's frequency in both the actual circuit and PSpice. The supply voltage increased in the circuit from 1.5 V in both the simulation and the actual circuit. The pulse width and voltage are different due to the different diodes used in PSpice circuit. The diode model used in PSpice differs from the LED in the circuit. The repetition rate is the same because the transistors and capacitors signal at the same time in both the simulation and LED circuit. In PSpice and the actual circuit, different capacitors were used to change the flash rate and pulse width of the LED. Capacitors changed the frequency and wavelength. Changing the frequency also changed the power and current going through the LED. Also, in PSpice, we changed the 3.3 k and 5.6 k resistors, which significantly change the flash rate. We noticed that the 5.6 k resistor changes the repetition rate more than the 3.3 k resistor, and that the two flash rate resistors act together in the circuit. The pulse width does not change very much when changing the resistors in PSpice. Voltage and current did not change at all in the process.

Finally, in PSpice, we discovered which components in the circuit consume the most power. We then tested this power dissipation by removing certain resistors, which would allow us to see a change in power dissipation. Current and power, through the diodes, can be controlled by the diode resistors. This means that diode current decreases with increasing resistance. These results allow us to control power rates in the circuit. Also, this data lets us limit the power used in the circuit, and allow us to use a very small amount of energy to turn on the LED flasher. We can observe how much power is needed to draw from the battery. We learned a lot about this circuit, including its limits, components, and the basic workings of the LED flasher.

This circuit is intended to be used as a sensor simulator to evaluate the power load from an isotope battery source.  To this end, we would like to easily reconfigure the circuit to draw a variety of power loads that range from 100 µW to 100 mW.  We can vary the circuit parameters to create this varying load.  The circuit elements that have significant control over power consumption are the capacitor, the diode resistor (limits current to output diode), and the repetition rate resistor (that varies the diode output repetition rate).  Unfortunately, variation of the capacitor affects both repetition rate and pulse width, making calculation more complex. Also, the capacitor and repetition-rate resistor do not change the power dissipation as much as the diode resistor (which limits the current).  We have calculated the circuit parameters for operation of the circuit over three decades of power load.  The results are shown in table 4.

Table 4.  The circuit power can be minimized by changing the capacitor, which modifies the signal repetition rate.

| **Power Dissipation** | **Capacitor (uF)** | **Diode resistor (ohms)** | **Flash rate resistor (k ohms)** |
|---|---|---|---|
| 100uW | 100 | 6100 | 8.9 |
| 1mW | 100 | 600 | 8.9 |
| 10mW | 100 | 52 | 8.9 |
| 100mW | 100 | 1 | 8.9 |

In this table, it shows that the capacitor and flash rate resistor can stay constant for the power dissipation to change.  The diode resistor controls the amount of current going through the diodes, which controls the power consumption of the diodes.  The measured results and parameter studies resulting from the modeling are expected to be used to evaluate several isotope batteries that are being developed for long-lived low-power sensors.

In the future, we will replace the diode pairs used in the simulation with a better model of the LED when modeling the circuit with PSpice.  In the experimental circuit, we would combine the two resistors that control the flash rate—5.6 k and 3.3 k resistors—in order to simplify the packaging.  Another possibility to investigate in the future is replacing the LED with an antenna. The measurement of radiated RF would follow using spectrum analyzers.

## List Symbols, Abbreviation, and Acronyms

| | |
|---|---|
| BJT | bipolar junction transistors |
| RF | radio frequency |
| LED | light-emitting diode |
| NRC | Nuclear Regulatory Commission |
| SiC | silicon carbide |

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